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Fuel-efficiency of hydrogen and heat storage technologies for integration of fluctuating renewable energy sources

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***Abstract* — This paper presents the methodology and results of analysing the use of different energy storage technologies in the task of integration of fluctuating renewable energy sources (RES) into the electricity supply. The analysis is done on the complete electricity system including renewable energy sources as well as power plants and CHP (Combined heat and power production). Emphasis is put on the need for ancillary services. Devices to store electricity as well as devices to store heat can be used to help the integration of fluctuating sources. Electricity storage technologies can be used to relocate electricity production directly from the sources, while heat storage devices can be used to relocate the electricity production from CHP plants and hereby improve the ability to integrate RES. The analyses are done by advanced computer modelling and the results are given as diagrams showing the system ability to integrate RES inputs between 0 and 100 percent of the electricity demand.**

***Index Terms* — Electrolysis, Electrochemical processes, Energy storage, Fuel cells, Hydrolysis, Power generation auxiliary systems, Power system modelling, Renewable energy, Sustainable energy systems, Wind power generation.**

I. Introduction

BOTH CHP and wind power are essential for the implementation of European Climate Change Response objectives, and both technologies are intended for further expansion in the upcoming decade. Meanwhile, wind turbines depend on wind and CHP depends on heat demand. Consequently, the production in some areas sometimes exceeds the demand.

The problem of balancing the variation in the consumer demands with the fluctuations in RES, such as wind power is well known and has been analysed thoroughly with focus on stand-alone systems and the integration of fuel cells and hydrogen systems [1-4]. Similar analyses have been made of the balancing of CHP electricity productions with restrictions in biomass fuels, grid connections and consumer demands including demand side management [5-8].

Meanwhile, there is a growing trend towards distributed electricity production and supply in Europe [9-11]. Therefore, many new problems will arise, in relation to management and operation of energy transfer as well as in relation to efficient distribution of wind power and other renewable energy sources in the grids [12-14]. Denmark is one of the leading countries in terms of implementing the combination of CHP, energy conservation and renewable energy. The primary energy supply has been kept constant for more than 30 years and today 50 percent of the Danish electricity demand is produced in CHP and approximately 20 percent is produced as wind power.

Already now the integration of wind turbines and CHP causes problems to the Danish electricity supply in terms of excess electricity production in certain hours. The problems are visible especially in the western part of Denmark, in which the share of small CHP plants and wind turbines are high. In several situations the excess electricity production together with bottlenecks in the transmission lines to the neighbouring countries has had a substantial influence on the market prices.

Previous studies have analysed how wind power can be better integrated into the electricity supply by investing in flexible energy systems such as heat pumps and heat storage capacities including small CHP plants in the balancing of supply and demand and in the supply of ancillary services. Also flexible demands and the integration of energy supply for transportation via electrical vehicles and hydrogen have been included in the analysis [15]. Based on such previous analysis the paper includes the analyses of electricity storage technologies based on hydrogen. The different storage technologies are studied, with the aim to reduce excess electricity production and reduce the consumption of fossil fuels.

II. Methodology

The possibility of integrating fluctuating renewable energy sources into the electricity supply is expressed in terms of the ability to avoid excess electricity production and the ability to reduce the consumption of fossil fuels in the energy system. The different means of solving the problems are analysed in the range of an electricity production from fluctuating renewable energy sources from 0 to 100 percent of the electricity demand.

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A. Energy System Analysis Modelling

The excess electricity production is found from detailed energy system analyses on the computer model EnergyPLAN. The model is an input/output model making annual analyses in steps of one hour. General inputs are demands, capacities and the choice of a number of different regulation strategies, putting emphasis on import/export and excess electricity production. Outputs are energy balances and resulting annual productions, fuel consumption and import/exports. The model emphasises the analyses of different regulation strategies, including ancillary service restrictions of different power and heat production units in order to secure grid stability in the electricity supply. For a detailed description of the model, please consult [16,17]. The model is available for downloading as a windows programme at: http://www.plan.aau.dk/~lund.

As part of this work the EnergyPLAN model has been modified. For a detailed description of the modifications, please consult [17].

In this paper the reference energy system is the western part of Denmark in the year 2020. The region is identical to the area of the transmission system operator Eltra. The reference is constituted by the following development: The electricity demand is expected to be 24.87 TWh in year 2020. Existing large coal-fired CHP steam turbines are replaced by new natural gas fired combined cycle CHP units when the old plants expire. The electricity production from CHP is as high as 50 percent of the demand. The reference is described in detail in [18]. The principle in the relationships between the different units in the reference energy system is illustrated in fig. 1.

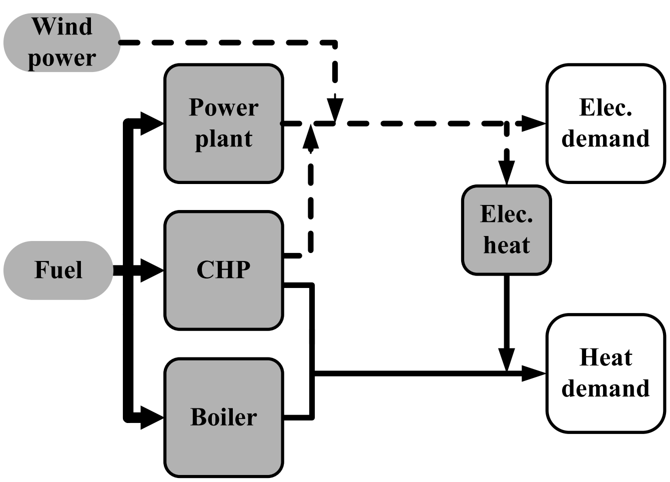

Fig. 1. The reference energy system.

The analysis has been made with the following restrictions in ancillary services in order to achieve grid stability: At least 30 percent of the power (at any hour) must come from power production units capable of supplying ancillary services such as power stations and CHP plants. At least 350 MW running capacity in big power stations must be available at any moment. Distributed generation from renewable energy sources is not capable of supplying ancillary services in the modelling, although this ability is added in a sensitivity analysis in the paper.

In the EnergyPLAN model the system is represented by more units in order to model the variations between large and small CHP plants etc. In fig. 1 the reference energy system consists of two energy flows and five power and heat producing units, being wind power, conventional coal fuelled power plants, natural gas fuelled CHP, boilers using oil and electric heating.

B. Alternatives analysed

The principles in the relationships between the different units in the three alternatives are shown in fig. 2 to fig. 4. The three following storage systems have been analysed:

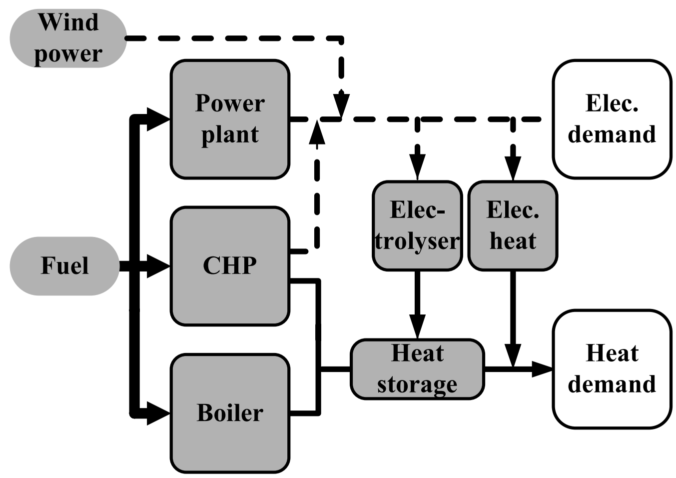

Fig. 2. Alternative 1: The heat pump heat storage system (HP/HS)

Alternative 1 (HP/HS): In this alternative heat pumps (HP) are used in combination with heat storage (HS) at the CHP systems. Such technology makes it possible to replace heat production from CHP units with heat pumps and consequently decreasing excess electricity production by decreasing CHP production and at the same time raise electricity consumptions in the heat pumps.

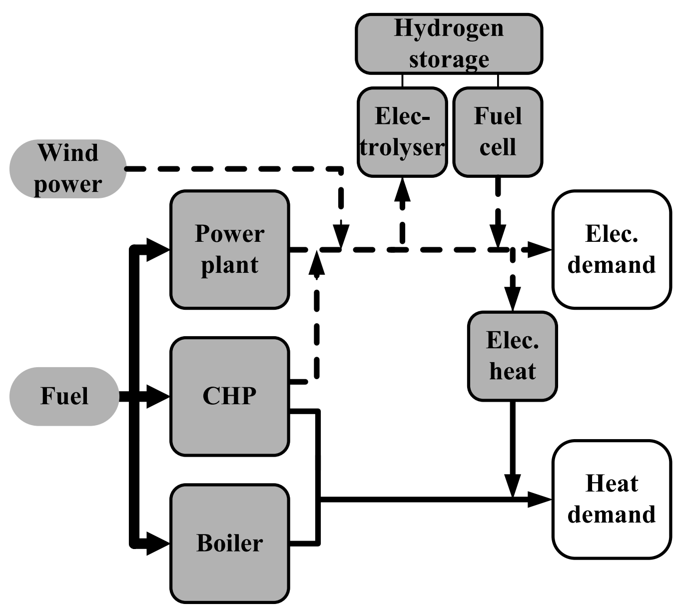

Fig. 3. Alternative 2: The electrolyser fuel cell system (EL/FC/H2S)

By adding heat storage such technology also makes it possible to reallocate CHP and heat pump production from one hour to another.

Alternative 2 (EL/FC/H2S): This alternative consists of electrolysers (EL) making hydrogen in combination with hydrogen storage (H2S) and fuel cells (FC). Such technology makes it possible to store excess electricity production as hydrogen. The system does not utilise the heat productions.

Alternative 3 (EL/CHP): Electrolysers are producing both hydrogen and heat for district heating in this alternative. The hydrogen is utilised in the CHP units and thereby utilised for both electricity and heat.

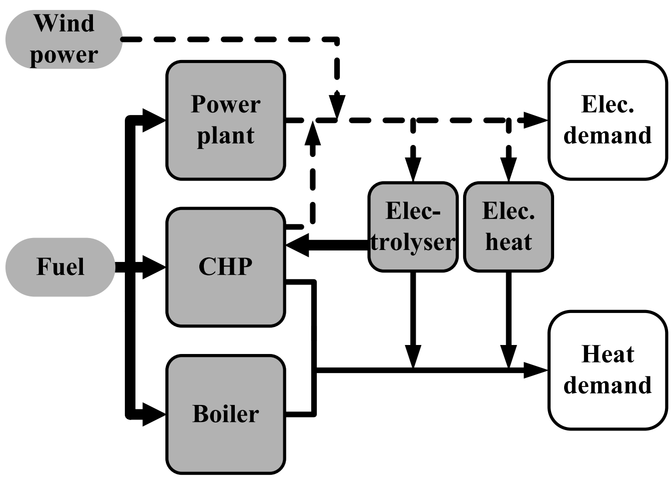

Fig. 4. Alternative 3: The electrolyser CHP system (EL/CHP).

C. Capacities used in the analyses

Each alternative has been analysed for two or three different capacities (see table 1). Please note that the capacity of the CHP-units in *alternative 3* is given in the reference energy system in the western part of Denmark year 2020.

TABLE 1
TECHNOLOGY CAPACITIES USED IN THE ANALYSES OF THE THREE ALTERNATIVES.

Alternative	Small	Medium	Large
1 – HP/HS	350 MW HP 40 GWh HS	700 MW HP 50 GWh HS	-
2 – EL/FC/HyS	1 GW EL 0.5 GW FC 100 GWh H2S	2 GW EL 1 GW FC 200 GWh H2S	3 GW EL 1.5 GW FC 300 GWh H2S
3 – EL/CHP	1 GW EL	2 GW EL	3 GW EL

D. Efficiencies used in the alternatives

The efficiency of the technologies in the reference system is well documented, as it consists of well developed technologies. In the reference system and in the three alternatives an efficiency for the best developed plants is used [18].

Electrolysers are commercially available with app. 80% efficiency, but more than 93% efficiency may eventually be possible [19-22]. The efficiency of storage devices for hydrogen is between 88% and 95% [23]. For use in large-scale systems such as energy systems solid oxide fuel cells are considered promising, partly because of their relatively high efficiency, and partly because of their ability to utilize more than one type of fuel [24]. For such fuel cells 60% power efficiency is considered possible when using hydrogen [25-27], though some studies show, that the efficiency may be higher when using other types of fuel [28] or when combining the fuel cells with gas turbines [29,30].

Here the analyses have been carried out for an electrolyser with a fuel efficiency of 80% in *alternatives 2 and 3*. In addition in *alternative 3* a heat efficiency of 15% in the electrolyser is used. For the fuel cell and hydrogen storage an efficiency of 60% in total has been used in *alternative 2*. In these analyses the heat from fuel cells is not utilized. In *alternative 3* the fuel from the EL is used in CHP-units with a power efficiency of 39% and a heat efficiency of 47% equal to the expected average efficiencies in the west Danish system in the reference year 2020 [18]. A 3.5 coefficient of performance (COP) of heat pumps is used as an annual average when taking the potential heat sources into consideration. The heat storage devises can store heat for fourteen days. The efficiencies used in the three alternatives are given in table 2.

TABLE 2
EFFICIENCIES OF TECHNOLOGIES USED IN THE THREE ALTERNATIVES. IN THE BRACKETS IT IS INDICATED IN WHICH ALTERNATIVE THE TECHNOLOGY IS USED.

Technology	Efficiencies
Heat pump (HP)	COP: 3,5 (1)
Electrolyser (EL)	Fuel eff. 80% (2,3) and heat eff. 15% (3)
Fuel cells (FC)	Electricity eff. 60%, incl. losses in H2S (2)
CHP	Power eff. 39% (3) and heat eff. 47% (3)

E. Presenting the results

The system's ability to integrate fluctuating renewable energy sources (RES) are illustrated in two different diagrams. The first diagram shows the annual excess electricity production as a function of the RES input in an *open* system. The less excess electricity production the better the system is. The second diagram shows the resulting fuel consumption in a *closed* system in which all excess electricity production is converted. The less fuel consumption the better the system is. The diagrams for the reference system are shown in fig. 5 and fig. 6.

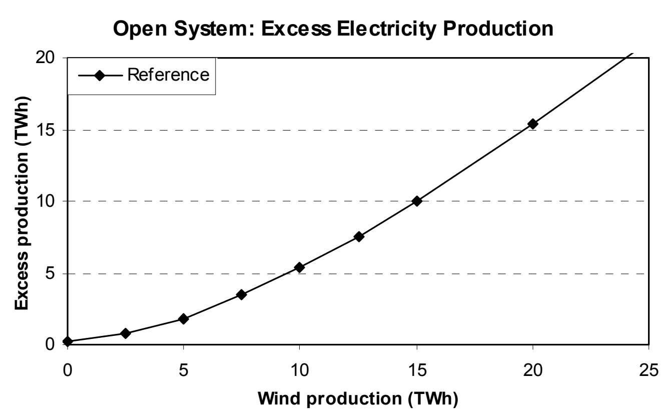

Fig. 5. Wind power production and excess electricity production in TWh in the reference system.

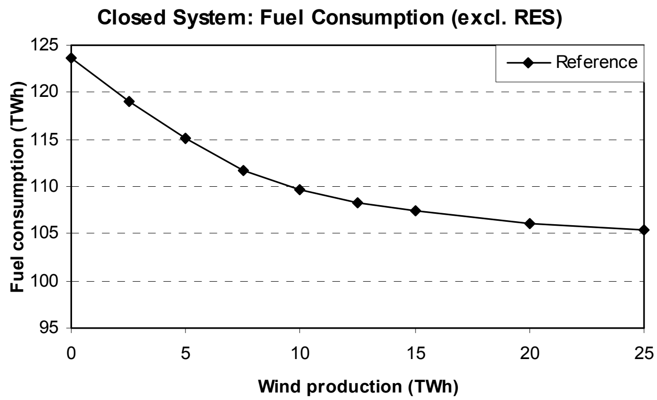

Fig. 6. Wind power production and fuel consumption in TWh in the reference system.

In both diagrams the x-axis gives the wind turbine production between 0 and 25 TWh equal to a variation from 0 to 100 percent of the demand (24.87 TWh). In fig. 5 the y-axis gives the excess electricity production in TWh. The less the curve raises, the better the integration of the renewable energy sources. In fig. 5 the analyses of excess electricity production is made in an open energy system in order to illustrate the capacity to integrate fluctuating renewable energy sources in the existing energy system.

As oppose to fig. 5 the closed energy system is illustrated in fig. 6. In the analysis made in fig. 6 there is no excess electricity production as a consequence of introducing a regulation strategy of converting or avoiding any excess production by the following means: First CHP production is replaced by boilers in the district heating systems, next excess electricity production is utilised for electric heating and finally wind turbines are stopped. The x-axis gives the wind production and the y-axis gives the primary fuel consumption of the entire energy system consisting of both electricity and heat productions as well as other services. The fuel consumption in fig. 6 excludes the primary fuel consumption from renewable energy sources, in this case wind power. The import/export is of course zero, as it is a closed system.

The methodology introduced in fig. 5 and fig. 6 is used for illustrating different technologies' ability to integrate fluctuating renewable energy sources in the next section.

III. RESULTS

In this section the results of the analysis conducted are presented. The analysis is divided into alternatives with small capacities, alternatives with medium and large capacities, combinations of alternatives and sensitivity analysis. Finally, the results are presented in a conclusion.

A. Analyses of alternatives with small capacities

When comparing the analyses of the three alternatives using the small capacities, EL/CHP *(alternative 3)* is the best alternative for reducing the excess electricity production in energy systems with large amounts of wind production (more than 10 TWh). HP/HS *(alternative 1)* handles RES four times better than the other two alternatives when the wind production is 5 TWh and is the best alternative for systems with wind production from 0 to 10 TWh. EL/FC/H2S *(alternative 2)* and EL/CHP reduce RES equally well with low amounts of wind production. The results of the analyses of the three alternatives using small capacities are presented in fig. 7.

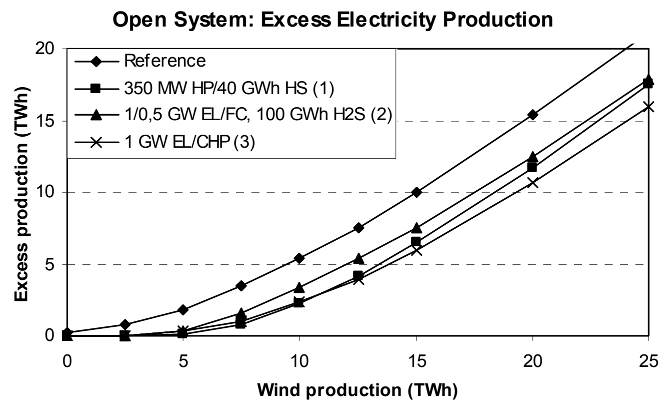

Fig. 7. Wind power production and excess electricity production in TWh in the three alternatives using small capacities.

Whereas the results of the analyses of excess electricity production in the three alternatives show that the differences are relatively small, the differences in the reduction in fuel consumption are more significant.

The HP/HS alternative is significantly better for reducing the fuel consumption than the other alternatives. The analysis even indicates that the reference system is better at reducing the fuel consumption than the alternatives using EL/FC/H2S or EL/CHP when the wind production is between 0 and 10 TWh. The reason for this is that these two alternatives have less efficiency in the energy conversion than the regulations strategy mentioned earlier, i.e. simply replacing CHP by boilers and converting excess production to heat by electric heating. The results of the analysis of the fuel consumption are illustrated in fig. 8.

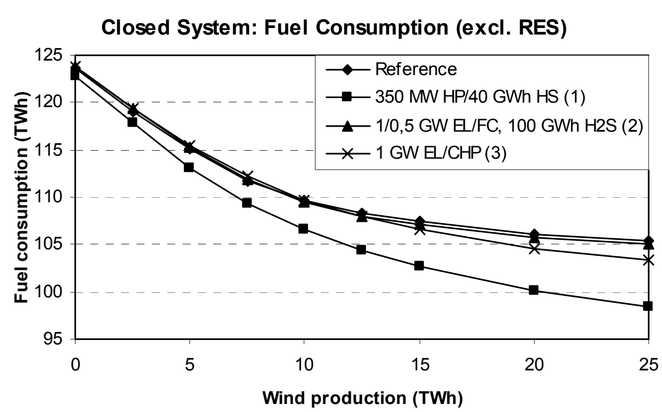

Fig. 8. Wind power production and fuel consumption in TWh in the three alternatives using small capacities.

B. Analyses of alternatives with medium and large capacities

When increasing the capacities of the technologies in the three alternatives, the analysis reveals that the alternatives have different strengths in different situations. The strengths are relative to whether a reduction in the excess electricity production is desired or a reduction in the fuel consumption is desired.

The results of the analyses of the three alternatives using medium capacities are presented in fig. 9. The best way of achieving further reductions in the excess electricity production will be to increase the capacities of the EL/CHP alternative.

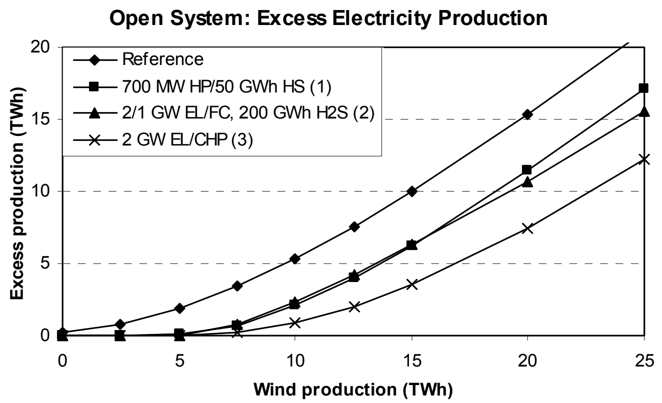

Fig. 9. Wind power production and excess electricity production in TWh in the three alternatives using medium capacities.

When analysing the small capacity alternatives in fig. 7 it can be concluded that the HP/HS alternative is to be preferred in a situation with less wind production than 10 TWh and the small EL/CHP alternative should be preferred for systems with more wind production. However, when making an overall comparison of all capacities, the EL/CHP alternative with the medium and large capacities proves to be best for reducing the excess electricity production.

If further reductions in the fuel consumption is desired the small HP/HS alternative should be preferred. When doubling the capacity in this alternative, the fuel-efficiency is only increased less than one percent; hence it would be more feasible to combine it with other technologies than to invest in further capacities than the small HP/HS alternative.

The reductions in fuel consumption of the medium capacities in the three alternatives are similar to the illustration in fig. 8. The HP/HS and EL/FC/H2S alternatives are less than one percent more efficient than the smaller alternative.

The medium and large EL/CHP systems reduce the fuel consumption marginally better when the wind production is between 10 and 25 TWh, as the reduction in the fuel consumption in this case is between one and three percent in the situation with 25 TWh wind production.

All capacities of the other two alternatives EL/FC/H2S and EL/CHP are, however, less efficient than the small HP/HS alternative for reducing the fuel consumption. It can in fact be concluded that when the wind production is less than 10 TWh, the EL/FC/H2S alternative does not reduce the fuel consumption relative to the reference system described in this paper, even when the capacities are three times as big as the EL/FC/H2S alternative in fig. 8.

Under the given conditions the analyses of reductions in fuel consumptions for different capacities does not change, that the HP/HS alternative is by far the best alternative as illustrated in fig. 8.

C. *Analyses of combinations of technologies*

In order to identify the strengths of the different alternatives, combinations have also been analysed. The overall result of this perspective is that the positive effects in relation to the reference system of the alternatives are accumulated as the technologies are combined. This is the case for both reducing the excess electricity production and reducing the fuel consumption. In fig. 11 and 12 the excess electricity productions and the fuel consumptions of the combined alternatives are presented.

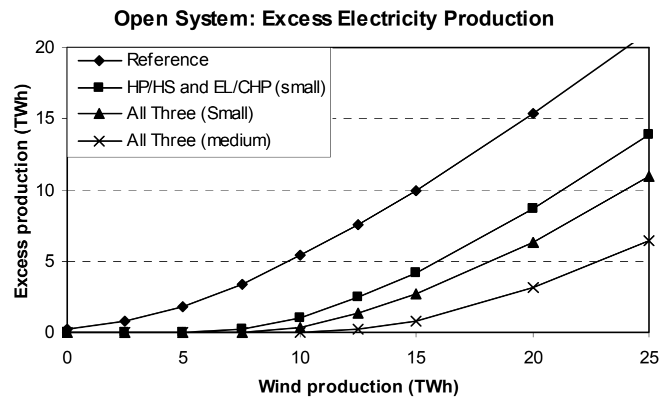

Fig. 11. Wind power production and excess electricity production in TWh in three combinations of alternatives using different capacities.

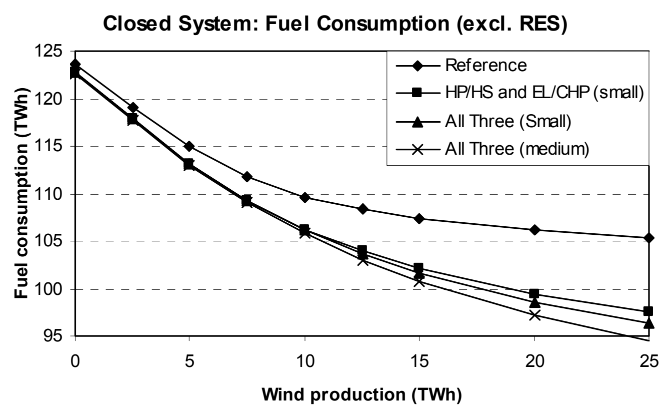

Fig. 12. Wind power production and fuel consumption in TWh in three combinations of alternatives using different capacities.

When this is the case, the positive aspects of each technology in relation to either the excess electricity production or the fuel consumption can be gained separately when introducing each technology. Generally there are none or few synergies when introducing more than one of the technologies in the reference system.

D. *Sensitivity analyses*

Electrolysers, heat pumps, heat storage devices and CHP-units are well developed technologies. On the other hand fuel cells and hydrogen storage devices are still in a developing phase. This means that the efficiencies used in the analysis in this paper are realistic for the electrolysers, heat pumps, heat storage devices and CHP-units and that the efficiencies used for the remaining two technologies, fuel cells and hydrogen storage devices are theoretical efficiencies.

Consequently, the results in the analysis above can be considered reliable, as the FC/EL/H2S alternative did not have the best effects neither on reducing the excess electricity production nor on reducing the overall fuel consumption.

Adding heat storage devices directly at the CHP-unit only improves the reduction in excess electricity production and fuel consumption very little in the analysis of this energy system and this regulation strategy. This is primarily due to the restrictions related to ancillary services, in which wind power is not included in such task. Meanwhile, combinations of wind power and electrolysers in an integrated system has the potential of including wind power in the task of providing ancillary service [31].

The ability to provide ancillary services with wind turbines using either EL/FC/H2S or EL/CHP has been analysed. As a result, the ability to reduce the excess electricity production by 10 TWh wind production is increased by 4 percent for EL/FC/H2S and by 6 percent for EL/CHP. With 20 TWh wind production the reduction is increased significantly for EL/CHP: 6 percent for EL/FC/H2S and 16 percent for EL/CHP. HP/HS is, however, still the best alternative for reducing the excess wind production with wind production lower than app. 10 TWh. The EL/CHP alternative is illustrated in fig. 13.

The reductions in the fuel consumption are also increased. The reductions are very similar for the EL/FC/H2S and the EL/CHP alternatives. The ability to reduce fuel consumption by 10 TWh wind production is increased by app. 1 percent and by 20 TWh wind production the reduction is increased by 6-7 percent.

The EL/FC/H2S and EL/CHP with wind turbine ancillary services are only marginally better than the HP/HS alternative without this possibility for reducing the fuel consumption when the wind production is higher than 15 TWh. When the wind production is lower than app. 15 TWh the HP/HS alternative is still the better alternative.

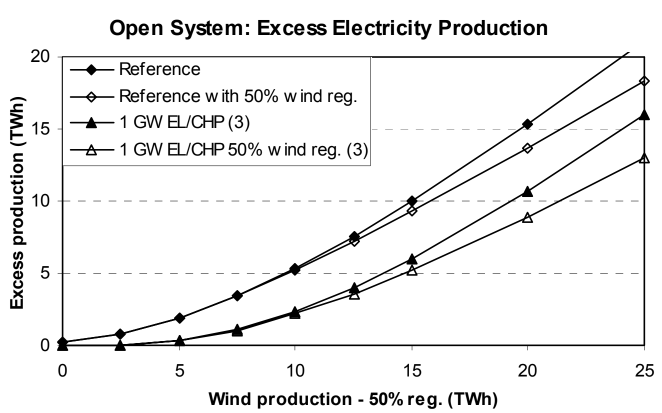

Fig. 13. Wind power production and excess electricity production in TWh for alternative 3 with and without wind turbines having the ability to provide ancillary services. Please note the reference with 50 percent wind regulation is for illustration only and is not possible, as it cannot provide ancillary services with wind turbines alone.

E. Conclusions

All of the three alternatives reduce the excess electricity production relatively well. However, when it is a closed system, there are significant differences in the ability to reduce fuel consumption. In this case the HP/HS alternative is significantly better than the other two alternatives EL/FC/H2S and EL/CHP.

Even when taking into account the possibility to use wind turbines for ancillary services, the EL/FC/H2S and EL/CHP alternatives are only marginally better for reducing the fuel consumption.

More technologies providing ancillary services are more important than increasing capacities as this only reduces the excess electricity production and fuel consumption marginally.

HP/HS should be used before taking the other alternatives described in this paper into consideration, both if the aim is to reduce the excess electricity production and to reduce the fuel efficiency.

The HP/HS alternative is a better alternative because it uses excess electricity production as well as reduces the CHP-units dependency on the consumers' heat demand.

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V. BIOGRAPHIES

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Henrik Lund has been associated professor at the Department of Development and Planning at Aalborg University in energy planning since 1993 and head of department from 1996 to 2002. Dr. Lund holds a PhD in "implementation of sustainable energy systems" (1990). His area of expertise has been energy system analysis, energy planning and energy economics for 20 years. The International Energy Foundation (IEF) gave him a gold medal for "Best Research Paper Award" within the area "Energy Policies &Economics" in 1998. He has been involved in a number of research projects and committee works in Danish energy planning, and in the implementation of various local energy projects in Denmark as well as in many other countries. In 2001 he was member of an expert group analysing "management of fluctuations in electricity production from renewable energy and CHP" conducted by the Danish Energy Agency for the Danish Parliament.